DEVELOPMENT OF A METHODOLOGY FOR UTILIZING INFRARED IMAGING TO ANALYZE THERMAL RESPONSE AND DIAGNOSE BREAST CANCER

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ABSTRACT

Breast cancer is among the diseases that kill the most women in Brazil and worldwide. The lethality of the disease is related to its stage, that is, to the degree of the disease's involvement in the individual. Early diagnosis is, therefore, of utmost importance to increase the chances of cure and patients' survival. The thermography exam, a safe method free of radiation exposure and physical contact, is capable of detecting the first metabolic alterations caused by a tumor. However, it provides only metabolic information and not anatomical information about the tumor, besides being strongly influenced by environmental factors (humidity, radiation, room temperature) and patient factors (age, breast shape and size). The objective of the work is, therefore, to develop a standardized method of using thermography through infrared imaging for the diagnosis of breast cancer. The method aims to provide anatomical information about the tumor, based on metabolic information from infrared imaging. For this purpose, breast imaging exams will be transformed into 3D STL models and subsequently smoothed and discretized using a uniform cubic mesh. The Method of Volume Elements divides the domain to be studied into control volumes, with each element of the mesh corresponding to a volume element of the breast. Using physical laws and empirical and theoretical correlations for mass, heat, and fluid flow, each volume element can be represented by a system of ordinary differential equations, which indicate the heat exchange and blood flow in each unit. In this way, the internal and surface temperature distributions of the breast as functions of time, space, and known initial and boundary conditions can be calculated. By comparing the obtained surface temperature of the breast and the actual infrared image temperature distribution of the breast, it will be possible to simulate the internal temperature distribution of the breast and obtain a precise estimate of the tumor location. This approach could make thermography more independent of complementary exams, as well as enable accurate early-stage cancer diagnosis and tumor depth prediction.

1. INTRODUCTION

Breast cancer stands as the most common malignant neoplasm among women, accounting for nearly 30% of all cancer cases in Brazilian women (INCA, 2020). Despite advancements in both diagnosis and treatment, breast cancer mortality remains significant due to late-stage detection, which not only hinders treatment but also reduces its effectiveness. Early detection is crucial for improving treatment success rates, as breast cancer has a cure rate of over 95% when diagnosed promptly (BRIOSCHI, 2016).

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Currently, the primary method for detecting breast cancer is mammography, which can detect small growths that are not perceptible to touch, thus enabling accurate diagnosis in the early stages of the disease (MORAIS, 2016). However, it still has limitations such as the use of ionizing radiation, which can cause long-term damage, as well as ergonomic and accessibility issues, excluding women with physical disabilities. Therefore, there is a need to search for a non-invasive screening technique that can assist in the early detection of breast cancer. Furthermore, it should be noted that prevalent imaging modalities such as mammography and magnetic resonance imaging (MRI) primarily offer anatomical information, allowing for visualization of the spatial arrangement and morphology of bodily organs and tissues.

One of the screening methods currently under study is thermography, which allows for mapping the temperature of the breast surface using infrared radiation. The examination provides metabolic information, specifically surface temperature data, where the hotter areas represent highly metabolic tissues. Thus, through skin temperature, it is possible to identify vascular and metabolic changes in the breasts that may be related to abnormalities (BRIOSCHI, 2016). Notably, thermography offers distinct advantages, such as its non-contact nature, absence of ionizing radiation, and absence of age restrictions.

However, thermography is not yet a definitive diagnostic method as it does not provide anatomical information about the tumor. Infrared imaging is still a relatively unexplored technology in medicine, as body temperature is strongly influenced by ambient temperature and individual metabolism.

Therefore, a standardized methodology for the use of infrared imaging in analyzing thermal response and diagnosing breast cancer would be of great utility in medicine. To achieve this, the research will employ 3D modeling and tools of numerical calculation and computational simulation to generate a simplified thermodynamic model of the breast. This will allow for estimating the internal temperature of the breast and locating the tumor.

2. THEORETICAL BACKGROUND

2.1 Volume Elements Model

In general, a mathematical model is designed to simulate the response or behavior of a real system on a computer, allowing for the calculation of the spatial and temporal distribution of any physical quantity within the engineering system under study (Vargas *et al.*, 2017). The approach used in the research is based on the Volume Element Method (VEM) proposed by Vargas *et al.* (2001). The major advantage of this method is that convergence can be achieved with reduced computational time by using a low number of elements. The proposed methodology consists of three main steps: discretization, equation formulation, and numerical solution.

In the discretization step, the system domain is divided into control volumes (CV). Next, in the equation formulation, the velocity field within the system domain is represented by algebraic equations based on the principles of mass conservation and momentum. Furthermore, an ordinary differential equation with respect to time is written to calculate each desired quantity at the center of each volume, resulting in a system of ordinary differential equations over time. Finally, an appropriate numerical method and computational code are chosen for obtaining the numerical solution (Vargas *et al.*, 2017).

The VEM allows for the existence of three types of elements in the same computational domain: solids, fluids, and mixed elements. It is possible for all types of elements to coexist in an integrated manner within the same region of the computational domain. For each of the possible interactions, the appropriate equations must be formulated (Vargas *et al.*, 2017).

A general volume element is represented in the Figure 1 below.

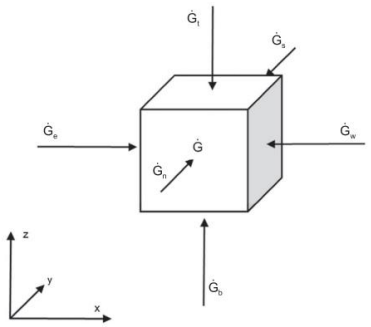

Figure 1. Typical Volume Element from Dilay et al. (2017)

The symbols $\dot{G}_e$, $\dot{G}_w$, $\dot{G}_t$, $\dot{G}_b$, $\dot{G}_N$, $\dot{G}_S$ represent the rates of transfer of the analyzed physical quantities with respect to time on the east, west, top, bottom, north, and south faces, respectively. The term $\dot{G}i$ can be used to represent heat generation, mass transfer, and the formation or degradation of a substance in a chemical reaction. Conservation equations can be written for a generic field ϕ in each control volume i as follows, as Eq. (1)-(2) shown:

$$\frac{d(\rho V\Phi)}{dt} = \sum_{j=e,w,t,b,n,s} \dot{G}_{j,i} + \dot{G}_i \qquad (1)$$

where t = time; ρ= density of the CV, V = volume of the CV and $\dot{G}_{j,i}$ is divided into two contributions.

$$\dot{G}_{j,i} = \dot{G}_{adv,j,i} + \dot{G}_{dif,j,i} \qquad (2)$$

with $\dot{G}_{adv,j,i}$ representing advective terms and $\dot{G}_{dif,j,i}$ representing diffusive (or conductive) terms, including

radiation and other types of interactions within the latter.

2.2 Adapted VEM for the human breast

Simplifying assumptions were adopted to reduce the mathematical complexity of the human breast model while still accounting for the major physical phenomena involved in the studied process. The breast was reduced to only two types of elements, representing two types of tissues: mammary tissue and blood tissue. Mammary tissue (VC_t) was considered as a stationary solid with no mass transfer, while Blood tissue (VC_s) was treated as a fluid in motion with constant flow. Additionally, there was no mass transfer between the blood and mammary tissue.

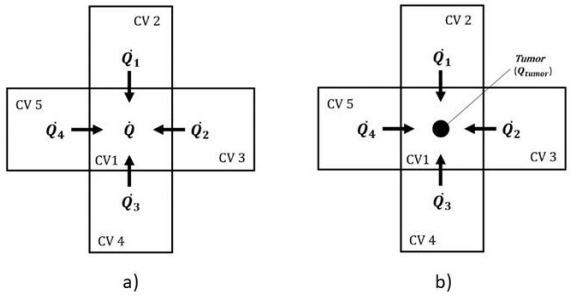

Figure 2. Contour conditions at a mammary tissue (VC_t) (Buabssi, 2021)

Initially, Figure 2 shows VC_t energy balance for two-dimensional discretization. Considering heat conduction between the volume elements within the mammary tissue, the following Eq. (3) was derived:

$$\dot{Q}_n = \frac{k\,A\,(T_n - T_1)}{d} \qquad (3)$$

Utilizing the relation $E = \rho . V . c_p . T$, it is possible to establish the rate of change of the temperature of VC_t with respect to time in the Eq. (4):

$$\frac{dT_t}{dt} = \frac{1}{c_{p,t}\,p_t\,V}\left(\sum \dot{Q}_n + \dot{Q}\right) \qquad (4)$$

where T_t is the temperature of the VC_t, t is time, $c_{p,t}$ is the specific heat of breast tissue, p_t is the breast tissue density and V is the volume of the VC_t.

For the case of a tumor, the heat generated by the natural metabolism of healthy tissues and the enhanced metabolism of the tumor must be taken into account. Therefore, by identifying these hotspots in the internal thermal image of the breast, it would be possible to estimate the distance between the skin surface and the geometric center of the tumor. The Eq. (5) demonstrate below:

$$\dot{Q} = \dot{Q}_{basal} + \dot{Q}_{tumor} \qquad (5)$$

where $\dot{Q}_{basal}$ represents the heat generated by the natural metabolism in healthy tissues, and $\dot{Q}_{tumor}$ represents the heat generated by the enhanced metabolism of the tumor.

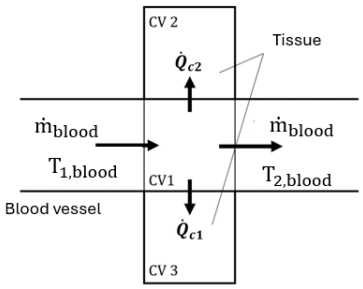

Figure 3. Contour conditions at a blood tissue (VC_s).

Furthermore, Figure 3 represents two-dimensionally the heat exchanges between a blood vessel (VC_s) and the neighboring control volumes. Considering heat convection from the blood to the mammary tissue, the following Eq. (6) was obtained:

$$\dot{Q}_c = h_s\,A\,(T_s - T_n) \qquad (6)$$

where h_s is the blood convection coefficient, A is the wall area of the cube, T_n is the temperature of the adjacent control volume, and T_s is the blood temperature.

Considering $\dot{m}_{e,j}$ and $\dot{m}_{s,j}$ as the mass flow rates at the inlet and outlet walls j, respectively, the relationship is shown d in Eq. (7):

$$0 = \sum_{j=e,w,t,b,n,s} \dot{m}_{e,j} + \dot{m}_{s,j} \qquad (7)$$

However, it is necessary to include blood perfusion in the relationship between inlet and outlet flow. Thus, we have Eq. (8):

$$\dot{m}_{e,j} = \dot{m}_{s,j} = \frac{p_{air} u_j A_j}{2} \qquad (8)$$

where p_{air} is the air mass density, u_j is the fluid velocity, and A_j is the area of face j. This means that the mass flow rate is considered both at the inlet and outlet, each contributing to half of the face.

Analogously to the previous case, the variation of the blood temperature with respect to time can be written as stated in Eq. (9):

$$\frac{dT_s}{dt} = \frac{1}{c_{p,s}\,p_s\,V}\left(-\sum \dot{Q}_c\right) \qquad (9)$$

where T_s is the temperature of the VC_s, t is time, $c_{p,s}$ is the specific heat of blood tissue, p_s is the blood tissue density and V is the volume of the VC_t. The negative sign is a consequence of the flow direction.

From these physical principles, the following system of ordinary differential equations (ODEs) is obtained, representing an initial value problem (IVP) that determines the distribution of the internal temperature field within the breast, given an initial value for time, as shown Eq. (10) below:

$$\frac{dT_t}{dt} = \frac{1}{c_{p,t}\, p_t\, V}\left(\sum \dot{Q}_n + \dot{Q}\right)$$

$$\frac{dT_s}{dt} = \frac{1}{c_{p,s}\, p_s\, V}\left(-\sum \dot{Q}_c\right) \qquad (10)$$

2.3 Breast properties

In the numerical solution step, the unknowns and parameters of the model are defined. In this case, the unknowns correspond to the internal temperatures of the control volumes (CVs). Additionally, it is necessary to arbitrarily determine the number of control volume elements and their respective volumes and define some parameters related to the thermophysical properties of breast tissues. The values to be used in the simulations are presented in Table 1:

Table 1. Thermophysical properties of breast tissue.

Tissue	**C [J/kg.K]**	**P [kg/m^3]**
Mammary	2300	920
Blood	3858	1059
Tissue	**K [W/m.K]**	**H [W/m^2.K]**
Mammary	0,21	x
Blood	x	65

Werner e Buse (1998); Ferreira e Yanagihara (1999).

Furthermore, Lozano *et al.* (2020) quantified the blood perfusion and the distribution volume of healthy and cancerous mammary cells, as shown in Table 2:

Table 2. Blood perfusion and distribution volume of healthy and cancerous mammary cells.

Cell	**Cell blood perfusion [ml/g.min]**	**Distribution volume [ml/g]**
Healthy	0,06	0,18
Cancerous	0,32	0,58

Lozano et al., (2020)

3. NUMERICAL SIMULATIONS

3.1. 3D MODEL OF THE HUMAN BREAST

In order to accurately locate the tumor through precise temperature distribution estimation, the computational simulation of the internal temperature distribution of the breast requires the construction of a simplified model of the human breast. To achieve this, imaging examinations such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) are initially performed.

Using the 2D images from these examinations, it is possible to generate a 3D STL file of the region of interest through three-dimensional medical image reconstruction software. In this case, the free and open-source software InVesalius, developed by the Renato Archer Research Center (CenPRA), is utilized. The software imports DICOM medical images (an international standard for image storage, exchange, and processing) and reconstructs them into three-dimensional (3D) images.

The model is obtained in the STL format, which is commonly used to represent three-dimensional models, by utilizing a mesh of connected flat triangles. However, the raw model may contain surface imperfections and noise. Therefore, post-processing is necessary, and for this purpose, the free 3D modeling and mesh editing software MeshMixer, developed by Autodesk, is employed. It allows for editing and manipulation of object meshes, surface reconstruction, and other related tasks.

Finally, the smoothed model is discretized using a uniform cubic mesh. This means that the model is divided into small cubes with uniform sizes, forming a grid that can be stored and manipulated on a computer. The ray tracing process involves determining luminance values for pixels through a backward scanning of the light path to each primary source. Each pixel belongs to a geometrically defined figure and can be represented within a system of equations (Schmid, 2004).

The whole process can be visualized in the Figure 4 below:

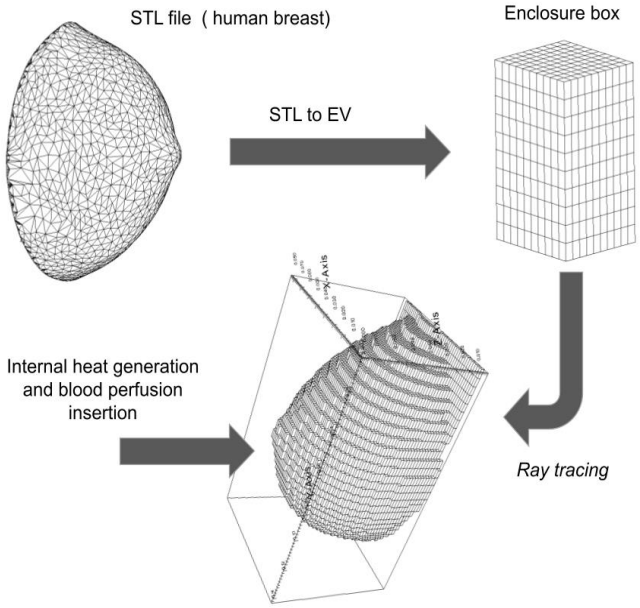

Figure 4: The mesh generation process.

3.2. DISTRIBUTION OF THE INTERNAL TEMPERATURE FIELD

To begin with, a computer program was written in FORTRAN to obtain the thermal response of tumors on the surface of the human breast. The Runge-Kutta/Felhberg method was used to integrate the system of equations in time, finding the steady-state solution to obtain the stationary temperatures at the center of each VE. Then, the Newton-Raphson method was used to solve the nonlinear system, which was linearized with respect to the unknown value at the center of the cell. (Dalmaso, 2021). The output data were opened in a program called Visit and ultimately visualized in the three-dimensional model developed.

The initial simulation involved a tumor with a radius of 0.001m, with the geometric center positioned at an arbitrary position, with coordinates x=0.04; y=0.04; and z=0.04. Subsequently, the simulation provided insight into the internal temperature distribution within the breast, yielding numerical outcomes from the system of equations detailed in Equation (11). It is possible to see a region of increased heat in the upper hemisphere of the breast (Figure 5), a result of heat transfer from the simulated nodule within. This is consistent with what is observed in practice, demonstrating that the process is capable of producing a result close to what is empirically found.

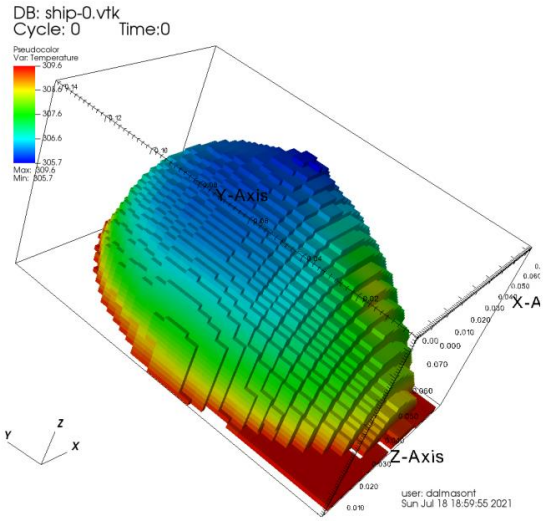

Figure 5. The distribution of the internal temperature field within the breast.

4. RESULTS AND COMPARISONS

To validate the proposed model, Buabssi and Dalmaso (2021) simulated a nodule measuring 2.0 x 0.9 x 1.7 cm, located in the lower lateral quadrant of the right breast at a depth of 4.7 cm. In the obtained image, the surface temperature in the region corresponding to the nodule was found to be 34.6 °C (307.7 K), as depicted in Figure 6.

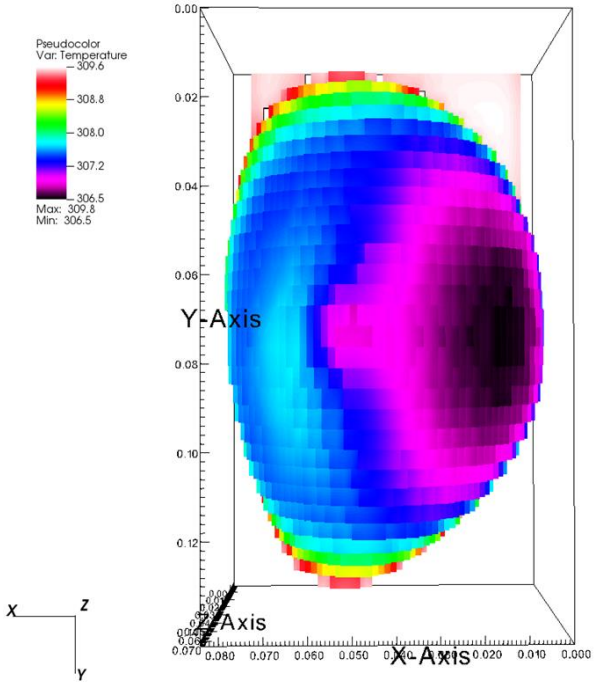

Figure 6. Front view of the breast temperature field obtained through simulation.

For the purpose of comparison, Figure 7 presents a thermographic image of a breast featuring a nodule with identical characteristics. Notably, the surface temperature associated with the biopsy-confirmed nodule corresponds closely to the temperature forecasted by the simulation.

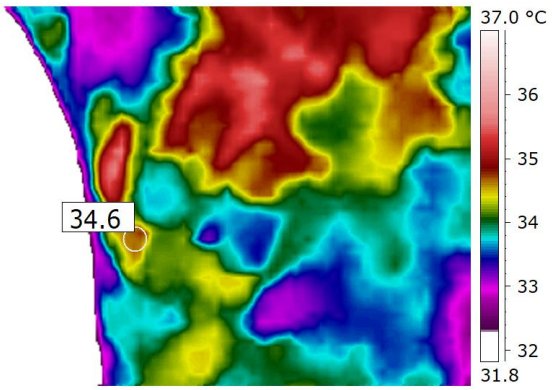

Figure 7. Thermographic image of the breast with the presence of a hyper-radiant nodule.

Figure 8 showcases the images of the cross-sections along the X, Y, and Z axes of this simulated nodule.

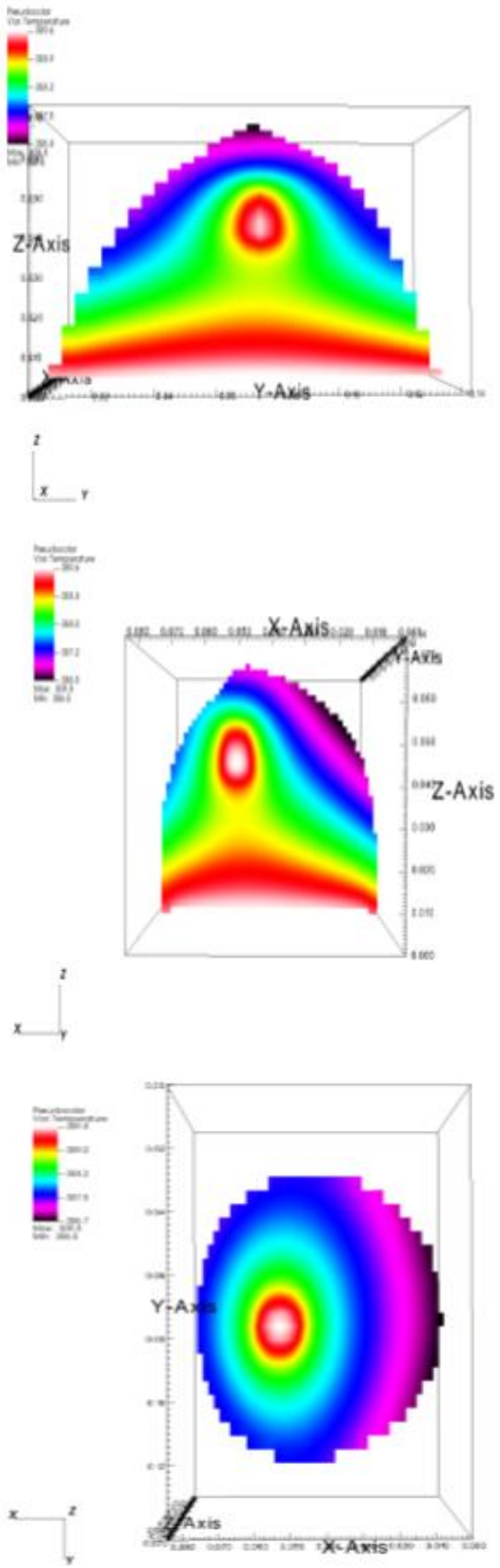

Figure 8. Cross-sections along the X, Y, and Z axes of this simulated nodule

Saccol and Dalmasso (2022) made a parametric analysis of the breast thermal response. Firstly, a healthy breast without a tumor was simulated. Afterwards, a tumor was replicated with a radius of 0.001m and its geometric center coordinates at (0.04, 0.04, 0.04). Subsequently, another tumor with the same size was simulated at different coordinates (0.01, 0.08, 0.04), attempting to locate the farthest tumor possible from the breast surface. In this case, the tumor was only visible when the model was sliced in the software, but the response on the surface of the breast did not visually indicate a significant change if compared to the healthy breast thermal response.

Although it had the highest temperature compared to the other tumor simulations, the surface temperature was similar to the case without a tumor. Finally, simulating a smaller tumor with a radius of 0.0002m at the same coordinates as the original tumor, it was not clearly visible on the surface, and it could only be visualized by slicing the model. However, in this case, comparing the results with the simulation without a tumor, the surface temperatures were higher, and the results were closer to the original tumor simulation**.**

The data can be visualized in the following Table 3 below:

Table 3. Simulation of the thermal response of the human breast

Radius of the tumor [m]	No tumor	0,001	0,001	0,0002
Location of the tumor [(x,y,z)]	No tumor	(0.04, 0.04, 0.04)	(0.01, 0.08, 0.04)	(0.04, 0.04, 0.04)
Lowest temperature on the surface [K]	304.9	305.7	305.0	305.5
Highest temperature measured [K]	309.9	309.6	310.1	309.6
Tumor's temperature measured on the surface [K]	X	308.6	did not show	did not show

5. CONCLUSION

In conclusion, this study has successfully developed a simplified 3-D mathematical model for analyzing the thermal response of the human breast. This model is the result of a comprehensive investigation involving theoretical, experimental, and numerical aspects. By adopting the volume element method, we've harnessed the advantage of a reduced-order model, which marries computational efficiency with precision. The simulations carried out have demonstrated a high degree of alignment with real-world examinations, with calculations converging in under 5 minutes.

Furthermore, it can be concluded that the tumor's size did not hinder the effectiveness of the simulations,

as even reduced sizes still exhibited an impact on the breast's surface temperature. However, concerning the tumor's depth from the surface, a limitation in thermal response was observed for tumors located deeper within the breast, as they did not show anomalies in surface temperature when positioned closer to the chest wall.

Looking ahead to future research endeavors, the acquisition of additional infrared breast images will be crucial. This will conduct a more comprehensive examination of real-world cases, thus affording a higher level of calibration and validation across diverse scenarios. This approach will be pivotal in accounting for variables such as breast size and patient age, fostering a more refined and accurate model for thermal responses within breast tissue.

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